REPORT DOCUMENTATION PAGE

AFRL-SR-AR-TR-03-

0225

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPOR... COVERED
		01 FEBRUARY 00 - 31 MARCH 03

4. TITLE AND SUBTITLE
CONTROL OF MIXING IN AEROENGINES USING MODERN DYNAMICAL SYSTEMS METHODS

5. FUNDING NUMBERS
F49620-00-1-0133

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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AFOSR/NM
4015 Wilson Blvd, Room 713
Arlington, VA 22203-1954

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
F49620-00-1-0133

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION AVAILABILITY STATEMENT
APPROVED FOR PUBLIC RELEASE, DISTRIBUTION UNLIMITED

20031001 242

13. ABSTRACT *(Maximum 200 words)*

In this project we have sought to understand and locate coherent material structures that govern turbulent fluid mixing. As we have showed, these structures coincide with invariant manifolds of the fluid particle dynamics. We have developed severa numerically assisted analytic criteria to extract invariant manifolds from simulated and measured flow data. Our criteria have been applied by others in analyzing controlled shear flows [I], vortex merger problems [2], geophysical data [3], and geological phenomena [4]. As an example, Fig. 1 shows coherent structures rendered by our criteria in a two-dimensional turbulence simulation.. Unexpectedly, we have also managed to extend Prandtl's classic steady flow separation criterion to unsteady flows. Remarkably, we also obtained explicit asymptotic formulae for unsteady separation profiles near a general no-slip boundary. As an example, Figure 2. compares a separation prediction from the widely used "zero-skin friction principle" (Fig. 2a), and from our unsteady separation criterion (Fig. 2b). Figure 3. (a) Instantaneous streamlines, separatior points predicted the classical theory (zero skin friction), and actual unsteady flow separation. Separation is visualized by plotting the current position of an initially horizontal layer of fluid particles in the oscillating separation bubble model of S. Ghosh (UTRC). (b) Same as (a), with our analytically predicted unsteady separation profile superimposed. In a new approacl to flow control, we have explored the use invariant manifolds to shape global coherent structures via local feedback control. We have applied these ideas in the control of advective mixing behind the flameholder of a combustor and the control of unsteady separation in bluff body shear flows (see Fig. 3).

14. SUBJECT TERMS	15. NUMBER OF PAGES
	4
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT

Final Report on

Control of Mixing in Aeroengines Using Modern Dynamical Systems Methods

AFOSR GRANT NO. F49620-00-1-0133
2000-2003

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Objectives and main results

In this project we have sought to understand and locate coherent material structures that govern turbulent fluid mixing. As we have showed, these structures coincide with invariant manifolds of the fluid particle dynamics. We have developed several numerically assisted analytic criteria to extract invariant manifolds from simulated and measured flow data. Our criteria have been applied by others in analyzing controlled shear flows [1], vortex merger problems [2], geophysical data [3], and geological phenomena [4]. As an example, Fig. 1 shows coherent structures rendered by our criteria in a two-dimensional turbulence simulation.

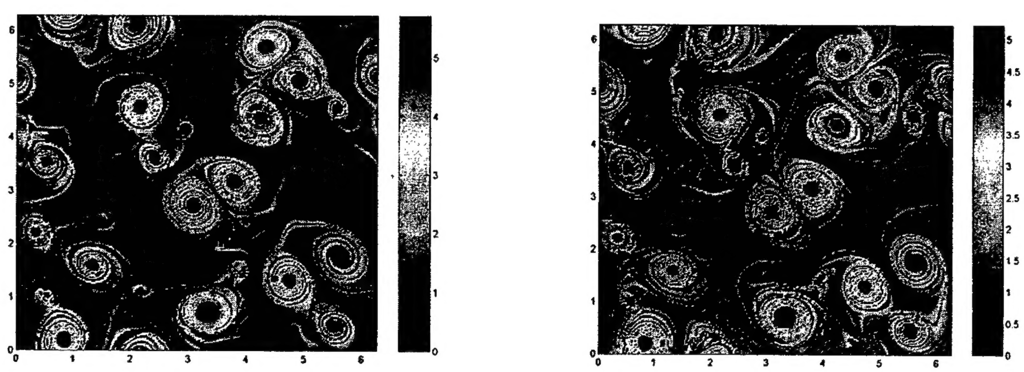
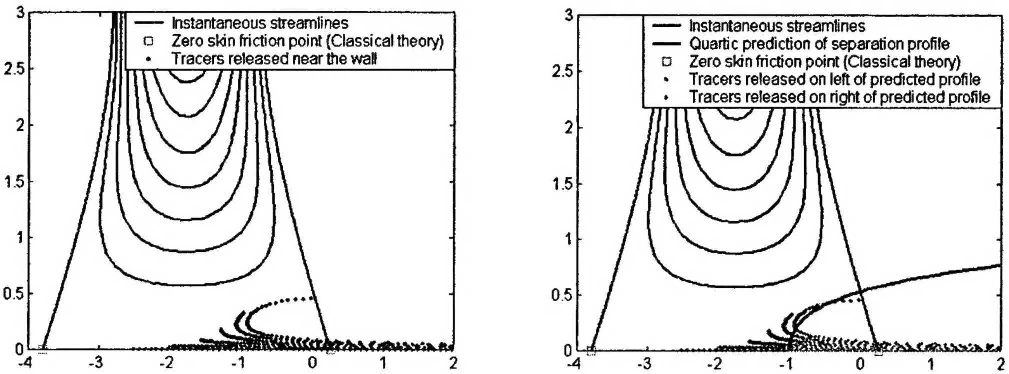


Figure 1: Repelling and attracting material lines at $t=0$, as extracted from a turbulence simulation.

Unexpectedly, we have also managed to extend Prandtl's classic steady flow separation criterion to unsteady flows. Remarkably, we also obtained explicit asymptotic formulae for unsteady separation profiles near a general no-slip boundary. As an example, Figure 2. compares a separation prediction from the widely used "zero-skin-friction principle" (Fig. 2a), and from our unsteady separation criterion (Fig. 2b).



(a) (b)

Figure 3. (a) Instantaneous streamlines, separation points predicted the classical theory (zero skin friction), and actual unsteady flow separation. Separation is visualized by plotting the current position of an initially horizontal layer of fluid particles in the oscillating separation bubble model of S. Ghosh (UTRC). (b) Same as (a), with our analytically predicted unsteady separation profile superimposed.

In a new approach to flow control, we have explored the use invariant manifolds to shape global coherent structures via local feedback control. We have applied these ideas in the control of advective mixing behind the flameholder of a combustor and the control of unsteady separation in bluff-body shear flows (see Fig. 3).

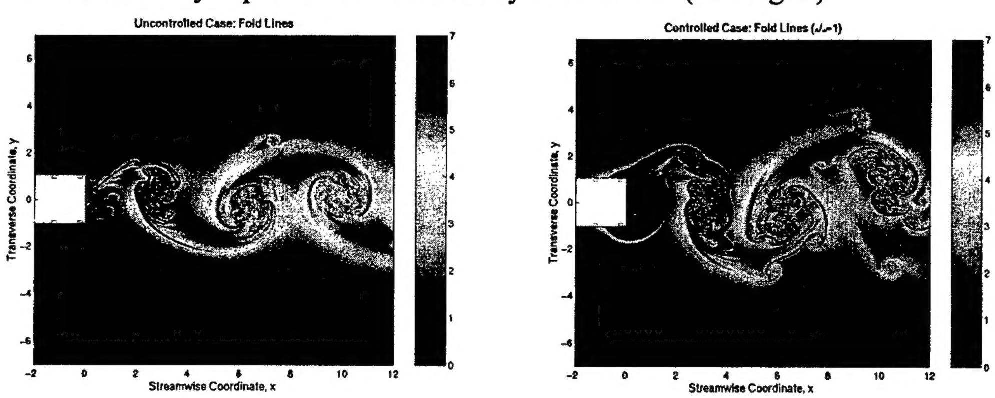
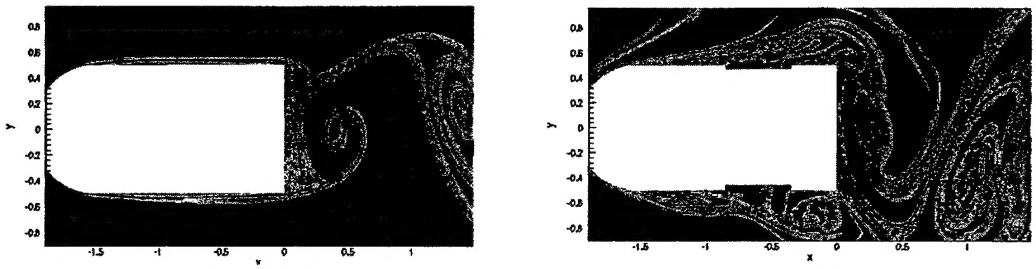


Figure 3. (1) Attracting material lines in the uncontrolled bluff-body vortex model (2) Same for the controlled model; the material lines emanating from the upper and lower walls are controlled to oscillate in a 1:1 resonance with the von Karman vortex-shedding frequency.

We have also made progress towards controlling heat release in aeroengines, and towards understanding three-dimensional unsteady separation. As an example, Fig. 3 shows the creation of unsteady separation profiles by active flow control in a Navier-Stokes simulation.



(a) (b)

Figure 3: Increased mixing induced by two pairs of facing horizontal jet actuators in a DNS model of a bluff-body flameholder. The contours show the value of finite-time Lyapunov exponents, whose maxima mark unstable manifolds (attracting material lines). (a) Uncontrolled flow. (b) Controlled flow.

Publications resulting from this grant

1. Haller, G., "Finding finite-time invariant manifolds in two-dimensional velocity fields", *Chaos* **10**, 99-108, 2000.

2. Haller, G., and Yuan, G.-C., "Lagrangian coherent structures and mixing in two-dimensional turbulence, *Physica D* **147** 352-370, 2000.

3. Haller, G., "Distinguished material surfaces and coherent structures in 3D fluid flows", Physica D **149**, 248-277, 2001.

4. Haller, G., "Response to the comments of Lapeyre, Hua, and Legras on `Finding finite-time invariant manifolds…' ", *Chaos* **11** 431-437 2001.

5. Haller, G., "Lagrangian coherent structures and the rate of strain in two-dimensional turbulence", *Physics of Fluids A*, **13** (2001) 3365-3385.

6. Haller, G., "Lagrangian coherent structures from approximate velocity data", *Physics of Fluids A*, **14** (2002) 1851-1861.

7. Voth, G. A., Haller, G., & Gollub, J. P., "Experimental measurements of stretching fields in fluid mixing", *Physical Review Letters.* **88** (2002) 254501

8. Wang, Y. Haller, G., Banaszuk, A. and Tadmor, G., "Closed-loop Lagrangian separation control in a bluff body shear flow model", *Physics of Fluids,* in press (2003)

9. Haller, G. Kinematic theory of unsteady separation for two-dimensional flows, *Journal of Fluid Mechanics*, submitted (2002).

10. Salman , H., Wang, Y., Haller, G., and Hesthaven, J. S. "A feedback control law for unsteady separation in two-dimensional flows", preprint (2002).

11. Liu, W., and Haller, G., "Strange eigenmodes and decay of variance in the mixing of diffusive tracers", *Physica D*, submitted (2003).

12. Haller, G., and Iacono, R., "Stretching, alignment, and shear in slowly varying velocity fields", *Physical Reviews E*, submitted (2003)

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For further details, please see the annual project reports.